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ROCKET PROPELLANT INPLACE FLOWMETER CALIBRATION SYSTEM, PROPULSION ENGINE TEST CELL (J-3)

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ARO, Inc.

May 1968

ROCKET TEST FACILITY
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AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The contents of this report are the results of the inplace flowmeter calibrations performed in Propulsion Engine Test Cell (J-3) to support the testing programs on the Aerojet-General Corporation, AJ10-137, liquid-propellant rocket engine testing sponsored by the National Aeronautics and Space Administration, Manned Spacecraft Center, under System 921E/9158.

The work described herein was performed by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under ARO Project Numbers RM1306, RM1356, RM1413, RM1607, and RM1630 during the period from May 1963 through February 1967. The manuscript was written under ARO Project No. RT8002 and was submitted for publication on January 19, 1968.

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The author wishes to acknowledge the invaluable collaboration in the preparation of this report by his associates J. L. Fergus, Jr., C. R. Bartlett, G. H. Schulz, and R. N. Haynes.

This technical report has been reviewed and is approved.

Marvin E. Burris Major, USAF AF Representative, RTF Directorate of Test	Roy R. Croy, Jr. Colonel, USAF Director of Test

ABSTRACT

The inplace flowmeter calibration system of Propulsion Engine Test Cell (J-3) is described, emphasizing the current equipment, calibration techniques, and the calibration results obtained. The system is a gravimetric pressure-fed propellant system which provides inplace calibration of turbine-type flowmeters with storable liquid propellants at the same temperatures, pressures, and flow rates experienced during rocket engine testing. Data from over 640 calibration data points have been statistically analyzed. Average absolute system errors for calibration with nitrogen tetroxide and a 50-50 hydrazine-UDMH blend were ±0.18 and ±0.21 percent, respectively, based on one standard deviation.

CONTENTS

SECTION I
INTRODUCTION

The complicated missions of liquid-propellant rocket engines today require an accurate knowledge of engine performance throughout the flight regime. Prior to flight, most engines undergo extensive static testing to determine performance. However, the accuracy of liquid-propellant rocket engine performance measurements ~~is~~ directly dependent on the accuracy of the propellant flow rates measured during testing.

Turbine-type flowmeters are normally used for flow measurement in liquid-propellant rocket engine testing because of their inherent accuracy, simplicity, and adaptability to this type of flow measurement (Ref. 1). However, turbine meters are sensitive to both the fluid viscosity and the differences caused by supply line configuration between flow bench plumbing and rocket engine plumbing immediately adjacent to the flowmeter.

To accurately determine the performance of the Apollo Service Module Engine (AJ10-137), a permanent inplace flowmeter calibration subsystem designed for use with nitrogen-based propellants was installed in the J-3 test cell complex (Fig. 1, Appendix I) for inplace calibration of turbine-type flowmeters. With this system, the flowmeters were calibrated in the line configuration with nitrogen tetroxide (N_2O_4) and Aerozine-50 (AZ-50) at the same temperatures, pressures, and flow rates that will exist during engine testing.

This report describes the current calibration technique and presents some of the latest calibration data obtained.

SECTION II
APPARATUS

2.1 SYSTEM DESCRIPTION

The flowmeter calibration subsystems installed in Propulsion Engine Test Cell (J-3) were designed for use with storable liquid propellants. The oxidizer subsystem has been used primarily for flow rates from 35 to 50 lb/sec and the fuel subsystem for flow rates from 20 to 35 lb/sec.

Each calibration subsystem is an integral part of the J-3 propellant system (Figs. 1 and 2), which also includes, for both oxidizer and fuel, a ground level propellant storage and transfer subsystem, a propellant

temperature conditioning subsystem, a cell mounted propellant tankage (F-3 fixture) with pressure control systems, and the test hardware flowmeter configuration. A tee was installed in the propellant supply line inside the cell between the flowmeter and the engine so that measured propellant flow could be channeled either to the engine for testing or to the flowmeter calibration system; therefore, the same plumbing configuration adjacent to the flowmeters could be used for either operation. Each calibration subsystem consisted of a diverter valve, a flow control venturi, a weigh tank, and the associated plumbing (Figs. 2 and 3). All propellant tank vent systems were connected to a neutralizing scrubber which discharged to atmosphere.

Propellants were temperature conditioned between 30 and 140°F, using a basic heat exchanger consisting of a 2800-gal tank containing a glycol/water solution. To obtain the low temperature, liquid nitrogen (LN_2) was used to cool the glycol/water solution, and to obtain the high temperature, steam was circulated through 0.5-in.-diam tubing coils located in the bottom of the basic heat exchanger containing the glycol/water solution. The conditioned glycol/water solution was then pumped to the heat exchangers located in the propellant barricades to condition the propellant as it circulated through the heat exchanger.

Both the oxidizer and fuel had two tanks each (one 1310 gal and one 1050 gal); these tanks, called the F-3 fixture tanks, were designed and fabricated to meet ASME pressure vessel code specifications. Two tanks (either oxidizer or fuel) are connected in series with a crossover line from the bottom of the smaller tank to the top of the larger tank. Pressurization was accomplished at the top of the 1050-gal tank using either gaseous helium (GHe) or gaseous nitrogen (GN_2). The propellant line from the (F-3 fixture) tank to the weigh tank and from the diverter valve to the storage tank is 4.0-in.-diam schedule 40 stainless steel. A cavitating venturi (Figs. 1b and 2) is located just upstream of the diverter valve and is designed to simulate the engine pressure drop experienced during engine firing. The 4.0-in.-diam line into the weigh tank contains a 3-ft flexible section to minimize the restraint imposed by the line and also to make any restraint repeatable. The 2.0-in.-diam dump line from the weigh tank to the ground storage tank contains a similar flexible section (1-ft) just upstream of the dump control valve for the same purpose.

Both the fuel and oxidizer 550-gal weigh tanks were constructed of 304 stainless steel. Each tank is mounted on a 20:1 beam balance which sits on a concrete platform (Fig. 4). During calibration, the accumulated propellant weight was obtained from a load cell installed in the linkage of the beam balance. The beam balance is periodically inspected and certified by a scale service organization to ensure proper operation and accuracy.

2.2 INSTRUMENTATION

The principal parameters required for flowmeter calibration with these subsystems were weigh tank weight, flowmeter output, weigh tank pressure, diverter valve position transient, and propellant temperatures. These primary parameters were used to calculate flowmeter constants generalized to lb_m fluid SG=1/flowmeter cycle.[1] Other parameters recorded for reference and for system operation were the F-3 fixture propellant tank pressures, propellant line pressure, propellant flow duration, ambient temperature, and barometric pressure. Table I (Appendix II) contains a list of the parameters recorded as well as the instrumentation used.

The F-3 fixture tank pressures and the weigh tank pressures were both measured with strain-gage-type pressure transducers and were recorded on null-balance potentiometer-type strip charts. Pressure fluctuations were limited to less than ±1.0 percent during calibration data points by automatic tank pressure control devices.

Propellant temperatures in the F-3 fixture tanks were measured with copper-constantan thermocouples, whereas the propellant temperatures in the lines (just upstream of the flowmeters) were measured with resistance temperature transducer (RTT) immersion probes. Both temperatures were recorded on direct-writing, continuously operating, strip chart recorders (and digital counters when desired).

Total flowmeter signal counts were fed through an Anadex® converter, which changes sinusoidal wave to a square wave, to a CMC® electronic digital counter for display. Flowmeter signal counts were totalized electronically from the diverter valve signal 1 to signal 2 (Fig. 5).

A light-beam-type oscillograph was operated during each calibration data point to provide a graphic record of the diverter valve position transients, flowmeter signal counts, time of the signals to the diverter valve, and the duration of the propellant flow to the weigh tank.

The weigh tank weight was measured with a strain-gage-type load cell (currently 500-lb_f rated capacity). The load cell analog output signal was converted to frequency form (20 to 80 kHz) and displayed on an electronic counter. Weight data resolution was on the order of ±1 count out of 10,000.

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[1]Generalized to a fluid of specific gravity = 1.0 for water at 4°C.

In all instances, the load cell, pressure transducers, thermocouples, and RTT's were laboratory calibrated prior to installation by using secondary standards traceable to the National Bureau of Standards (NBS).

When a permanent record was desired, all parameters were recorded on magnetic tape.

SECTION III
PROCEDURE

3.1 WEIGH SCALE CALIBRATION

The load cell installed in the linkage of the 20:1 beam scale was in-place calibrated by applying deadweights to the scale platform to obtain a scale factor and to determine the linearity and repeatability of the system. Weights were applied in 800-lb increments up to a total of 3200 lb_f.

During flowmeter calibration, propellant was flowed into the weigh tank with the tank vents closed to prevent any loss of weight by propellant vaporization. Therefore, it was necessary to establish the effect of tank pressure on the indicated tank weight. This was determined by maintaining various known pressure levels (GN_2 or GHe) in the weigh tank while repeating the deadweight loading and unloading sequence.

The deadweights used to calibrate the weigh scale were certified at AEDC in accordance with NBS criteria. Weight corrections for local gravity and air buoyancy were also made.

3.2 FLOWMETER CALIBRATION WITH PROPELLANTS

Each flowmeter was calibrated with water at AEDC prior to installation in the inplace calibration system. Water calibration data were used primarily to determine the linearity and repeatability of the flowmeter prior to installation.

Before recording calibration data, the propellant was flowed from the pressurized F-3 fixture tank through the flowmeter and diverter valve to the ground storage tank for approximately 3 min. During this time, the diverter valve was periodically actuated. The purpose of this pre-calibration propellant flow was to bleed in the system, check the diverter valve operation, flex the weigh scale system, and temperature condition the system, thus minimizing any gradients in propellant temperature during the first data point.

For each calibration point, propellant flow was established from the pressurized F-3 fixture tank through the flowmeter and the diverter valve to the ground storage tank. When steady-state flow was established, the diverter valve was actuated so that propellant flowed to the weigh tank for a fixed time period. The diverter valve was then actuated again so that flow was diverted to the ground storage tank, and then flow was terminated.

The weigh scale reading (less the zero load and corrected for the effect of weigh tank pressure) represented the accumulated propellant weight. Total flowmeter signal counts represented the flowmeter output from the time the signal was given to divert the flow to the weigh tank (signal 1, Fig. 5) until the time the signal was given to divert the flow to the ground storage tank (signal 2, Fig. 5). The total flowmeter counts were corrected for diverter valve transients using the oscillograph record of the flowmeter output and the diverter valve transient (Fig. 5). Analysis has shown that the flow rate to the weigh tank is directly proportional to the valve position. The diverter valve opening and closing times were approximately 0.3 and 0.4 sec, respectively. The average total cycles during the diverter valve transient were approximately 0.10 percent for oxidizer and 0.15 percent for fuel of the total flowmeter cycles at nominal flow rates for a 60-sec propellant flow data point.

A flowmeter constant (in lb-H_2O/cycle) was determined from each data point based on the net weight of propellant accumulated in the weigh tank, corrected totalized flowmeter cycles, and propellant specific gravity based on the propellant temperature at the flowmeter. The propellant specific gravity as a function of temperature was determined in the ESF Chemical and Metallurgical Laboratory using a propellant sample obtained from the sump tank prior to each calibration series. A typical flowmeter constant calculation procedure is presented in Appendix III.

Prior to the next data point, the weigh tank was drained (to the ground storage tank) and vented. A small quantity of propellant (30 to 40 lb) was retained in the weigh tank to ensure a slight pre-loading of the weigh scale system.

The initial inplace calibration of each flowmeter typically consisted of 21 data points at four flow rates which span the flow rates to be used during engine testing. Calibrations prior to each rocket test period consisted of seven data points, which were considered sufficient to validate or invalidate the flowmeter performance when compared with the initial calibration data.

SECTION IV
RESULTS AND DISCUSSION

The results of over 650 calibration data points have been statistically analyzed, and the results are summarized in Tables II and III.

An average absolute error in the flowmeter constant was obtained by averaging the absolute errors from each flowmeter calibration system. The average absolute errors in flowmeter constant thus obtained were:

1. ±0.18 percent (1σ) with N_2O_4 and
2. ±0.21 percent (1σ) with AZ-50.

Turbine-type meters are sensitive to propellant viscosity; therefore, calibration with liquids other than the propellants to be used during rocket engine testing is not satisfactory. A comparison of inplace calibration data obtained with propellant with data obtained with water (Figs. 6 and 7) indicates that the bias between the results is not predictable, either in direction or magnitude (Ref. 2). Thus, using the results of flowmeter calibrations performed with fluids other than those to be used during testing is generally very unsatisfactory.

The possible sources of error are discussed in relationship to the overall flowmeter calibration system accuracy in the following sections.

4.1 EFFECT OF PROPELLANT TEMPERATURE

The temperature of the propellant can have two distinct effects on the flowmeter which affect the flowmeter constant. The first effect is a consequence of the variation of propellant viscosity with temperature. The other effect is the unequal expansion or contraction of adjoining parts of the flowmeter, which results in changes in mechanical friction and flowmeter flow area.

The majority of the flowmeter calibrations performed with the J-3 inplace flowmeter calibration systems has been with ambient temperature propellants; however, to date, four calibration series have been performed at approximately 110°F and three calibrations at 40°F with both N_2O_4 and AZ-50. There was no discernible change in the flowmeter constant due to different propellant temperatures between 40 and 110°F.

No calibrations were performed with N_2O_4 in excess of 120°F because the weigh tank pressure would exceed the safe operating design limit of 50 psia. Calibration with AZ-50 at temperatures below 30°F is not feasible because it ceases to be miscible.

4.2 ACCURACY OF THE INPLACE FLOWMETER CALIBRATION SYSTEM

The flowmeter calibration constant (lb-H_2O/cycle) is subject to systematic errors, random errors, and the error in specific gravity due to temperature measurement error (Ref. 3). An error is also introduced through the accuracy of the chemical analysis used to determine specific gravity versus temperature. However, this error does not affect the accuracy of the calculated engine flow rates provided the flowmeter calibration is performed with the propellant at the same temperature as during testing. If the engine firing is made with the propellants at a different temperature from that obtained during calibration, then an error is introduced in the calculated flow rates if the slope of the specific gravity is not the true slope.

In estimating the error in the flowmeter calibration constants determined with the J-3 flowmeter calibration system, consideration has been given the errors in:

1. The deadweights used to calibrate the weigh scale system,
2. The weigh tank weight reading,
3. The adjusted weigh tank weight due to the error in the weigh tank pressure correction,
4. The propellant temperature measurement which affects the value of the specific gravity,
5. Totalized flowmeter cycles, and
6. Adjusted totalized flowmeter cycles due to the error in the diverter valve transient correction.

The total error of the flowmeter constant was then estimated by taking the square root of the sum of the squares of the above errors in conjunction with the precision of the flowmeter constants referenced to the equation of the mean line as a function of flowmeter frequency. The method used to calculate the total error in flowmeter constant is presented in Appendix IV.

4.2.1 Error in the Deadweights

The deadweights used to calibrate the weigh scale were calibrated by ESF, and the calibration is traceable to the NBS. Corrections for local gravity and air buoyancy were also made. The best estimate of the one standard deviation in the weight of the deadweights was 0.001 percent.

4.2.2 Error in Weigh Tank Weight Reading

The load cell in the weigh tank scale system is periodically calibrated using the deadweights. This deadweight calibration was repeated four times during each weigh scale calibration. Based on the calibrations performed for the Apollo testing, the average best estimates of the error in the weigh tank weight reading were ±0.139 and ±0.100 percent (1σ) for the fuel and oxidizer subsystems, respectively.

4.2.3 Error in Weigh Tank Pressure Correction

The linearity and repeatability of the pressure effect on indicated tank weight was determined during weigh scale calibration by varying the deadweight loading while maintaining constant weigh tank pressure and by varying the pressure while maintaining constant deadweight loading.

The best estimate of the error in weigh tank pressure reading was ±0.5 percent (1σ). The reflected errors in propellant tank weight for typical calibration data points were ±0.004 percent (1σ) for oxidizer and ±0.001 percent (1σ) for fuel. In view of their magnitudes, these errors have been considered insignificant in calculating the absolute system error.

The average best estimates of the error (1σ) in adjusted weigh tank weight due to the error in the correction made for the weigh tank pressure were ±0.069 and ±0.060 percent for oxidizer and fuel, respectively.

The average best estimates of the total error in the weigh tank weight reading were obtained by statistically combining the error in the weight reading (Section 4.2.2) with the error in the weigh tank pressure correction (Section 4.2.3). The average best estimates of the total error (1σ) in the oxidizer and fuel weigh tank weight readings based on four calibrations of each were ±0.122 and ±0.160 percent, respectively (see Tables II and III).

4.2.4 Error in Propellant Temperature Measurement and Specific Gravity

Any error in measuring propellant temperature at the flowmeter results in an error in specific gravity and consequently affects the flowmeter constant (Ref. 3). The best estimate of the one standard deviation in propellant temperature (RTT) at the flowmeter was ±0.5°F.

By using

$$\frac{\Delta SG}{\Delta T} = 0.0012 \text{ for } N_2O_4 \text{ (Oxidizer)}$$
$$= 0.0005 \text{ for AZ-50 (fuel)}$$

$$SG_{ox} \text{ at } 70°F = 1.4440$$
$$SG_{fuel} \text{ at } 70°F = 0.9025$$

the resulting best estimates of the 1-σ errors in specific gravity (70°F) were:

$$\sigma SG_{ox} = \sqrt{\left[\frac{0.5 \times 0.0012}{1.4440} \times 100\right]^2}$$

$$= \pm 0.041 \text{ percent for the } N_2O_4$$

$$\sigma SG_{fuel} = \sqrt{\left[\frac{0.5 \times 0.0005}{0.9025} \times 100\right]^2}$$

$$= \pm 0.028 \text{ percent for the AZ-50}$$

4.2.5 Error in Totalized Flowmeter Cycles

The CMC counters are accurate to ±1 cycle out of 10,000. This has been considered negligible when compared with the 25,000 to 60,000 flowmeter cycles for a 60-sec calibration data point.

4.2.6 Error in Totalized Flowmeter Cycles Due to Error in Diverter Valve Transient Correction

The average net diverter valve transient correction is 50 cycles, estimated to be accurate to ±2 cycles out of 25,000 to 60,000 cycles (60-sec calibration data point); thus, this error has been considered negligible.

4.2.7 Precision of the Flowmeter Calibration Data

During the period from January 1965 through January 1967, 30 flowmeter calibration series were run with both the oxidizer and fuel flowmeter calibration systems. There were approximately 315 data points

obtained with the oxidizer system and approximately 330 with the fuel system. The flowmeters used with N_2O_4 and AZ-50 were calibrated for flow rates from 35 to 50 lb/sec and 20 to 35 lb/sec, respectively. The average precisions of the data about the mean were ±0.12 and ±0.11 percent (1σ) for oxidizer and fuel, respectively.

A summary of the precision of the flowmeter data is presented in Tables II and III.

4.2.8 Absolute System Error with Oxidizer and Fuel

The absolute system error of the oxidizer and fuel inplace flowmeter calibration systems is estimated by considering the aforementioned errors in conjunction with the precision of the flowmeter data. A summary of the results of performing this statistical analysis on the data obtained from the calibrations performed during Apollo testing in test cell J-3 is presented in Tables II and III. The average absolute errors (1σ) in the flowmeter constants obtained were ±0.18 and ±0.21 percent for the oxidizer and fuel, respectively. Appendix III indicates the method used to calculate the absolute error in flowmeter constant.

SECTION V
SUMMARY

The J-3 inplace flowmeter calibration system was designed and developed by AEDC-RTF personnel to support testing of the Apollo Service Module engine (AJ10-137). Accurate measurement of propellant flow rates was required to document engine performance. The results obtained are summarized as follows:

1. Thirty flowmeter calibration series (approximately 315 data points) using N_2O_4 resulted in an average precision of ±0.12 percent (1σ).
2. Thirty flowmeter calibration series (approximately 330 data points) using AZ-50 resulted in an average precision of ±0.11 percent (1σ).
3. The average absolute error in the flowmeter constant obtained with N_2O_4 was ±0.18 percent (1σ).
4. The average absolute error in the flowmeter constant obtained with AZ-50 was ±0.21 percent (1σ).

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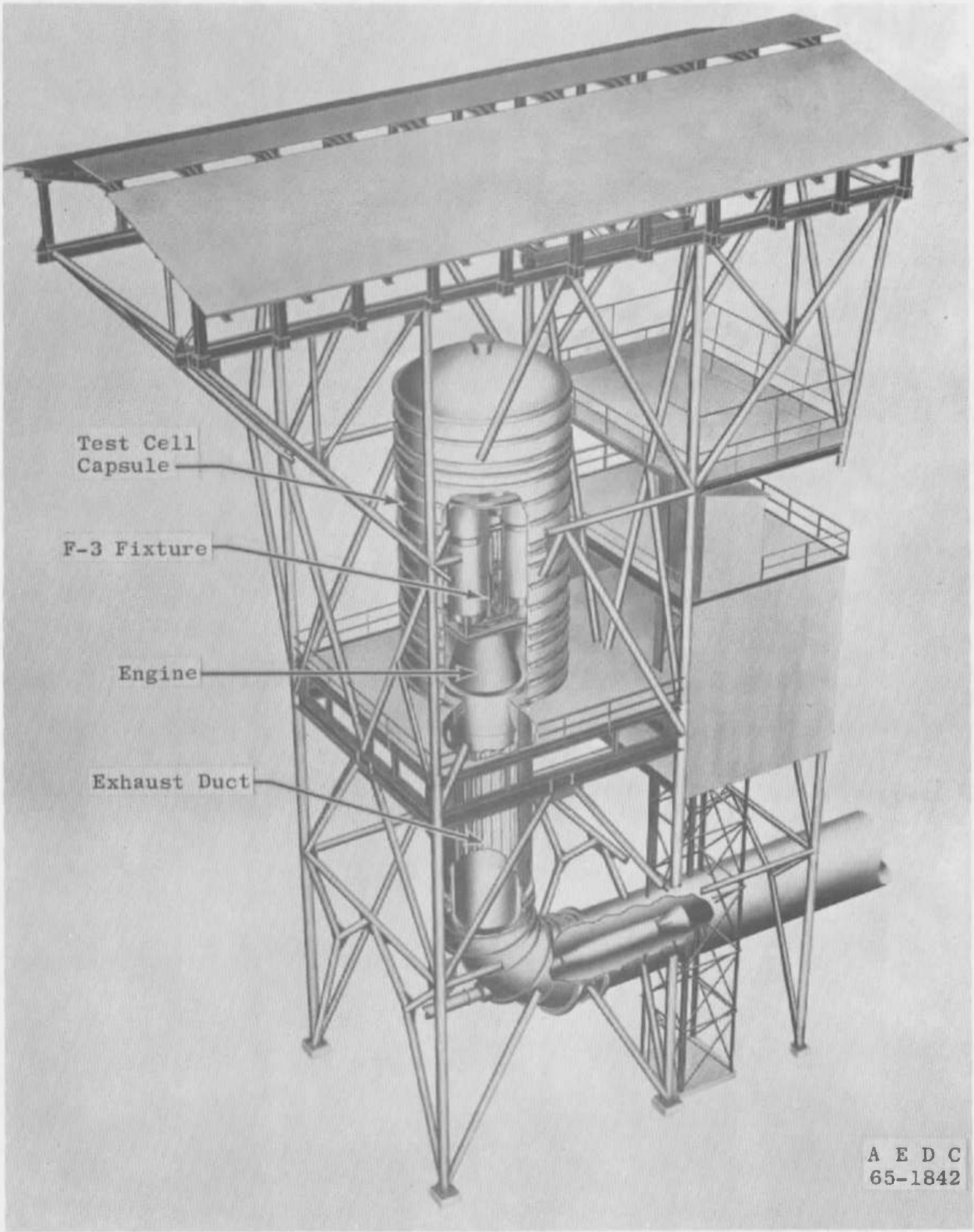
2. Barton, D. L. "An Inplace Flowmeter Calibration System for Use with Noncryogenic, High-Vapor-Pressure Liquids." AEDC-TR-67-27 (AD808512), March 1967.

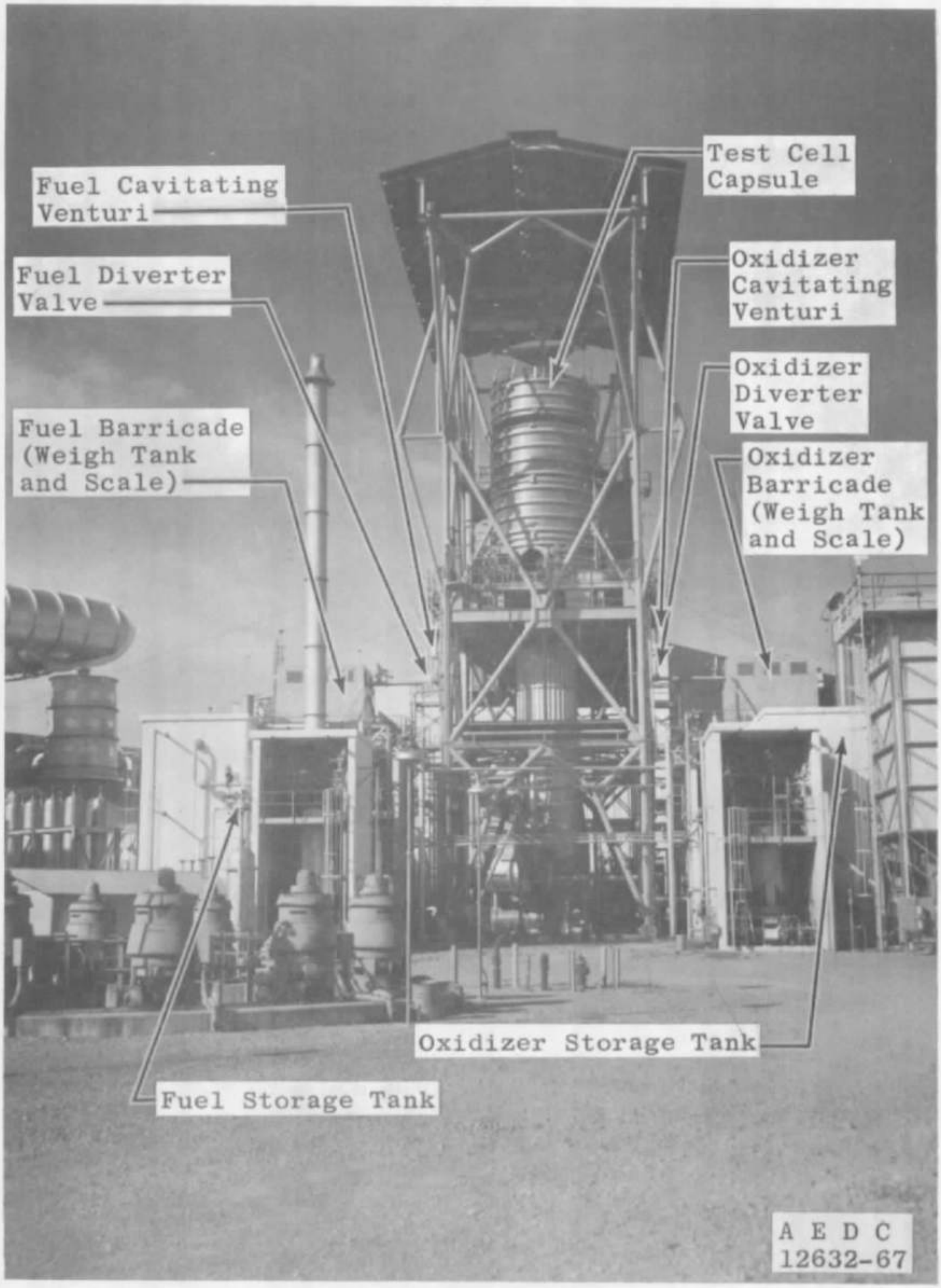
3. Bartlett, C. R. "An Analysis of the Accuracy of Liquid-Propellant Rocket Engine Performance Measurements in the Satellite Rocket Cell J-3." AEDC-TDR-62-207 (AD290495), December 1962.

APPENDIXES



a. Cutaway of Capsule and Ducting

Fig. 1 Propulsion Engine Test Cell (J-3)



b. Location of Calibration System Components

Fig. 1 Concluded

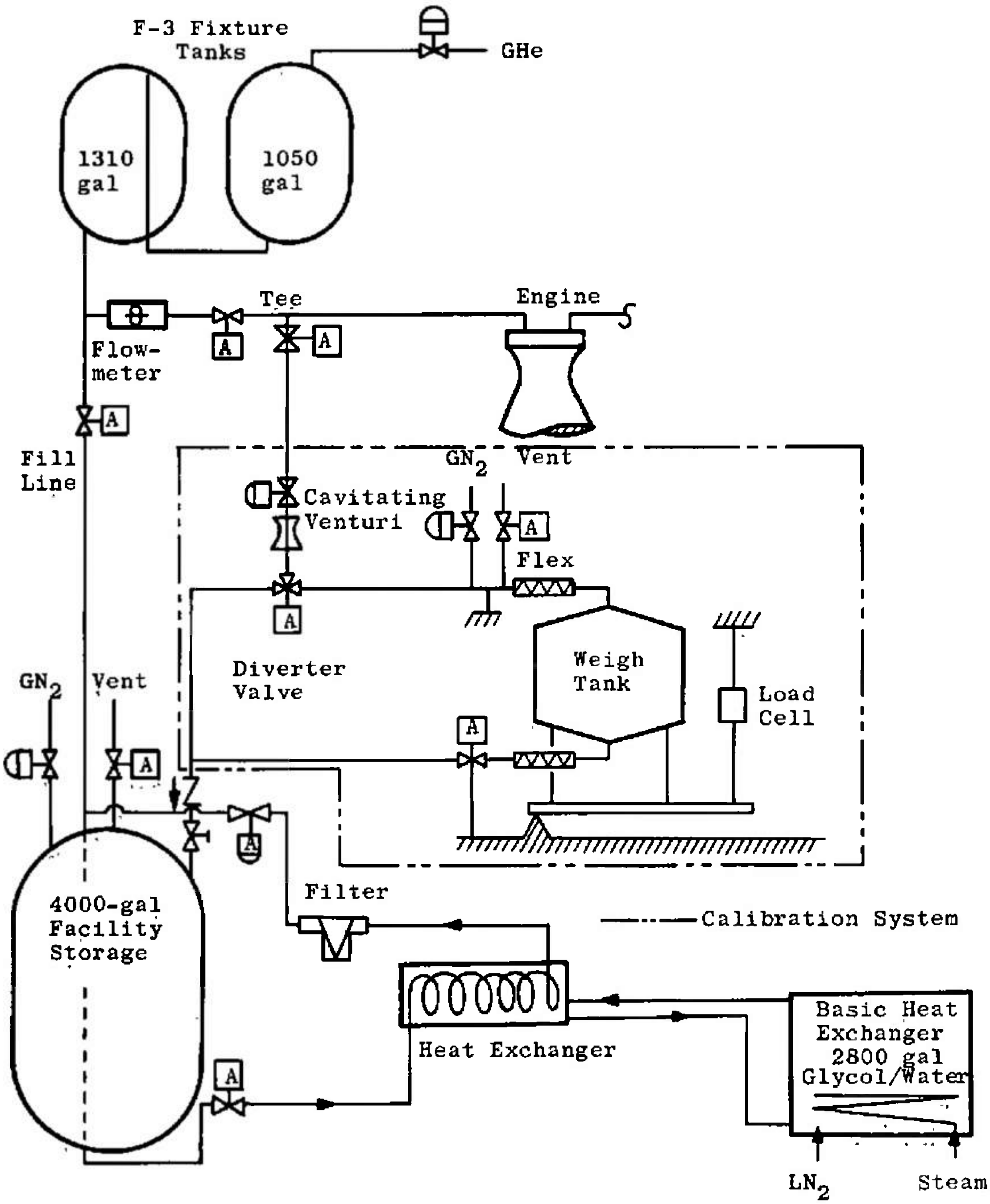


Fig. 2 Schematic Diagram of Typical J-3 Inplace Flowmeter Calibration Subsystem

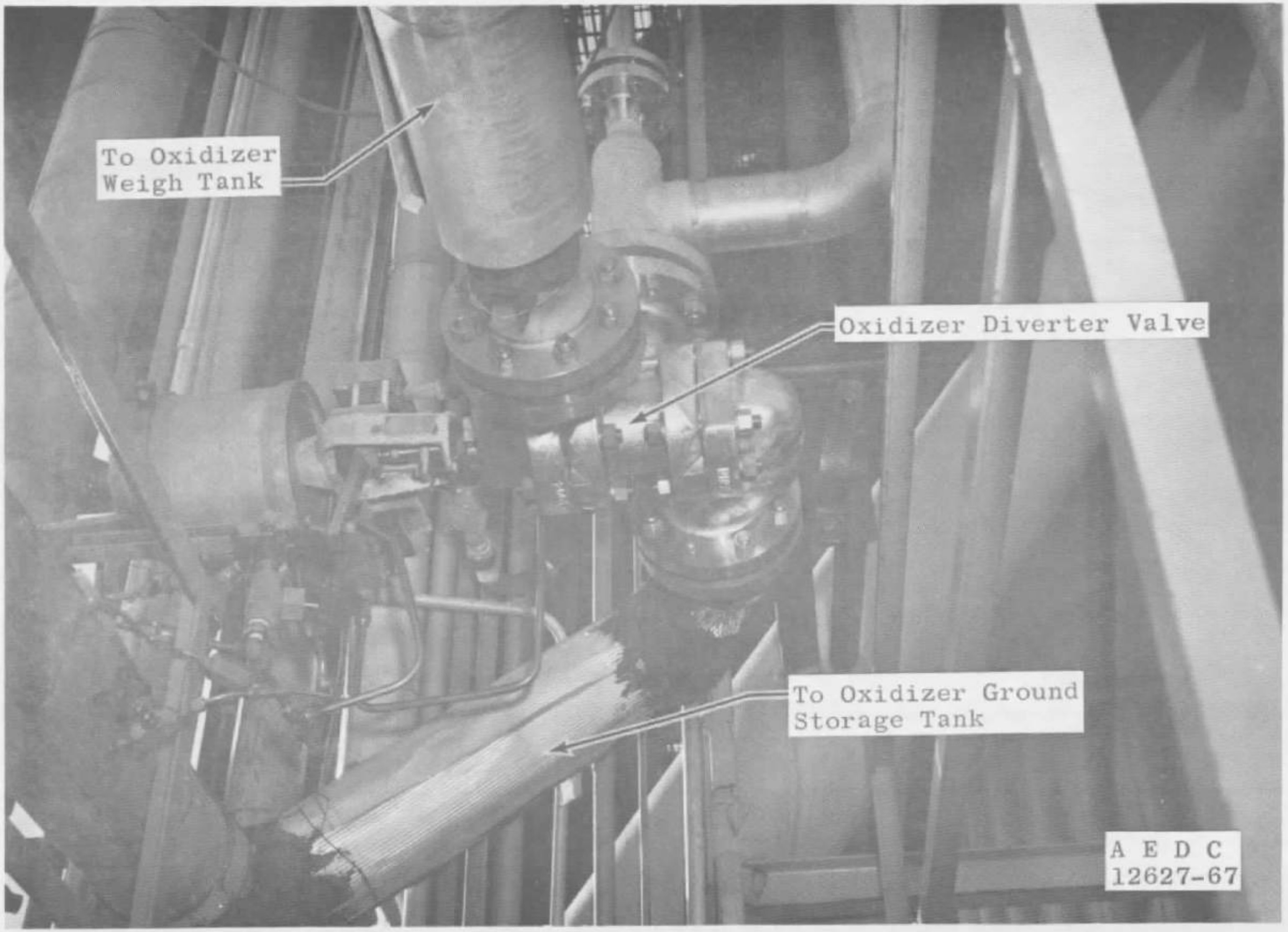


Fig. 3 Oxidizer Diverter Valve Installation

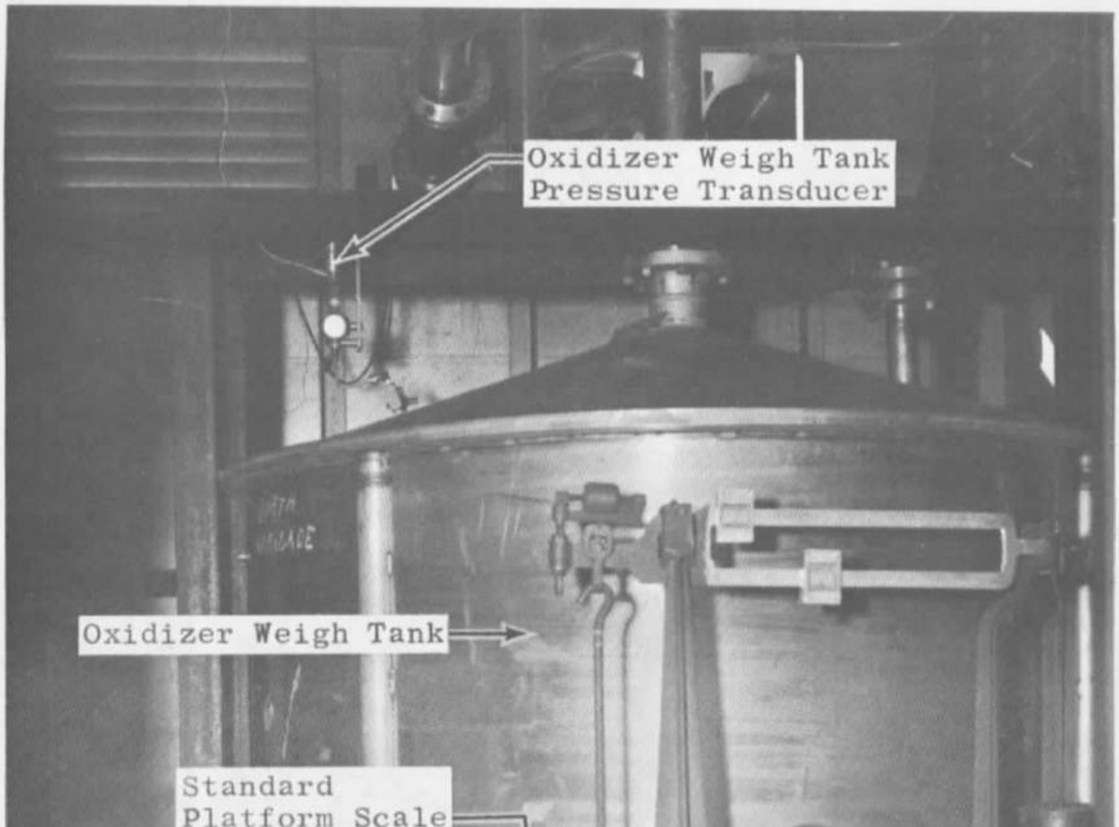


Fig. 4 Oxidizer Weigh Tank and Weigh Scale System

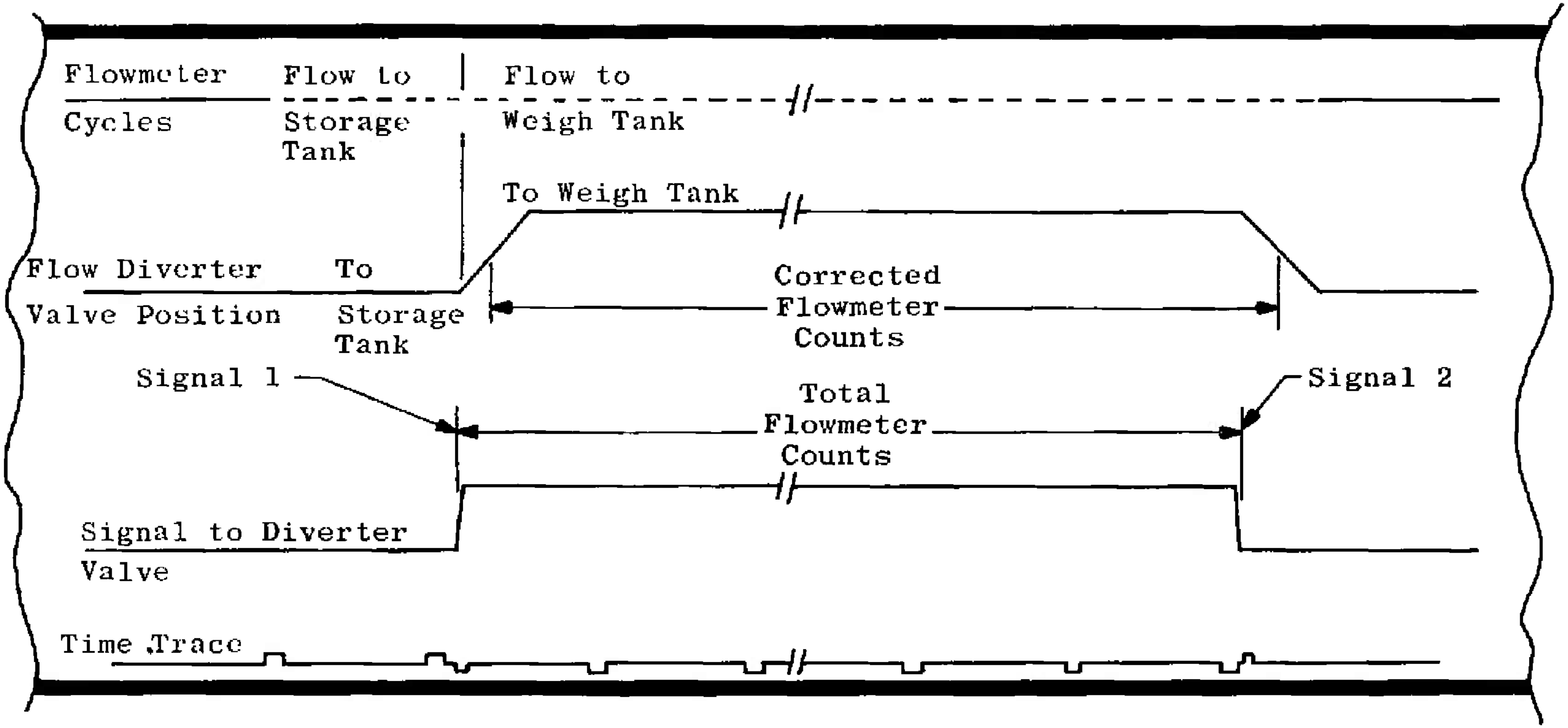


Fig. 5 Typical Oscillograph Trace

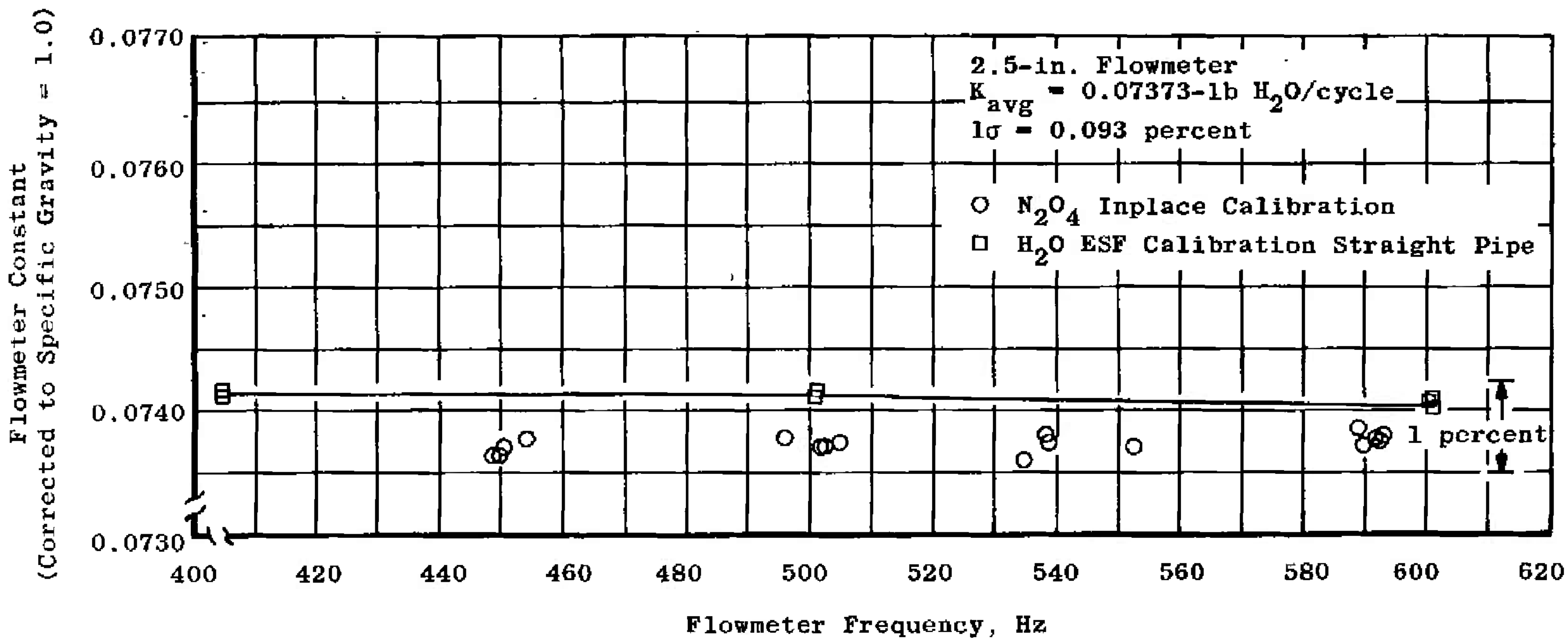


Fig. 6 Typical Flowmeter Calibration Data Using N_2O_4

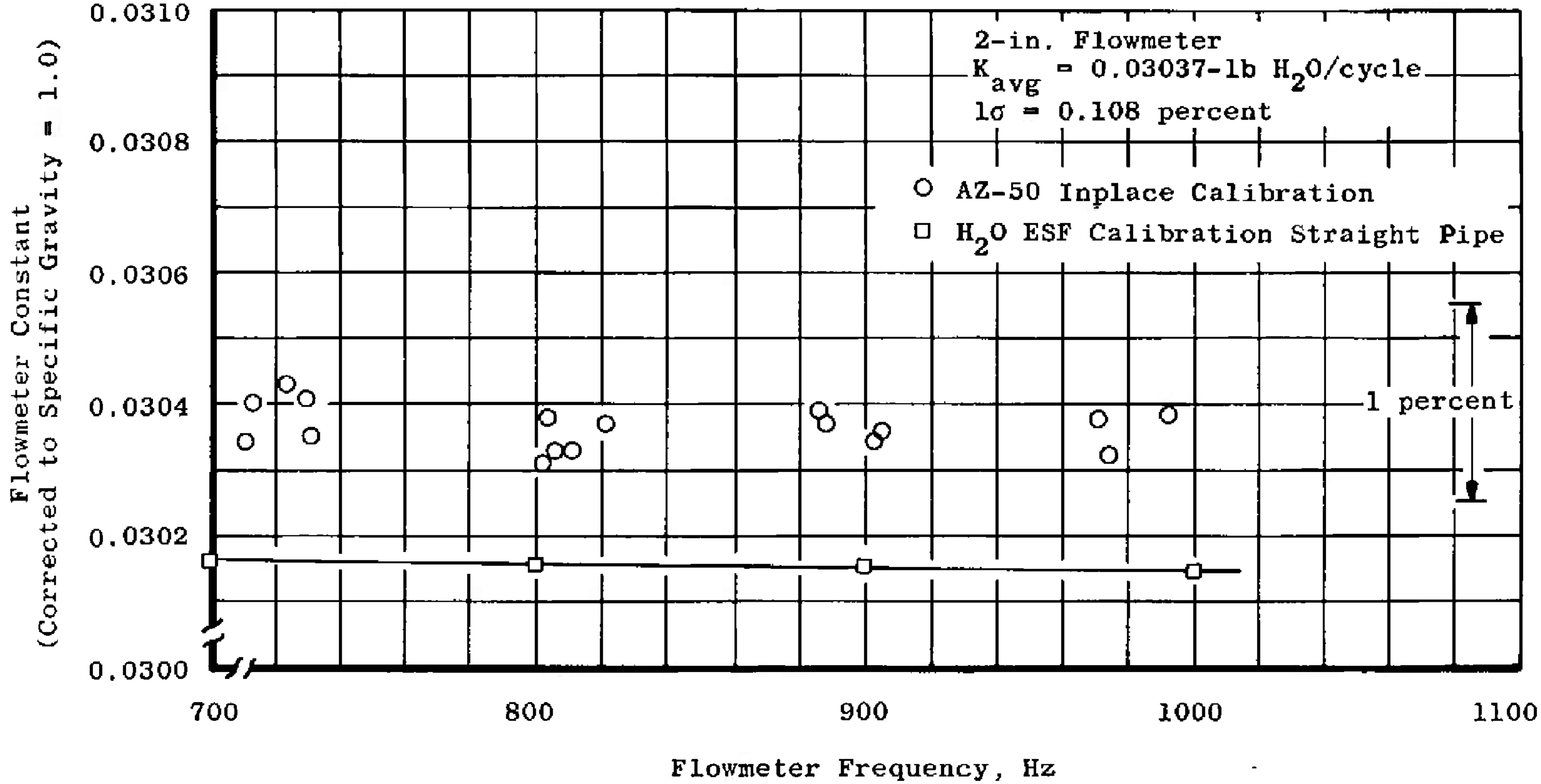


Fig. 7 Typical Flowmeter Calibration Data Using AZ-50

TABLE I
INSTRUMENTATION

Parameter	Measuring Device	Range	Recording Methods	Estimated Accuracy at Nominal Level (1-σ)
Flowmeter Output	Turbine-Type Flowmeter Induction-Type Coil Pickups	---	Frequency Output Converted to Pulse Signal and Recorded: a. Manually from Digital Counter and/or b. On Magnetic Tape and c. Oscillograph	±1 count
Weigh Tank Weight	Strain-Gage-Type Load Cell	0 to 3000 lb	Analog Output Converted to Pulse Signal and Recorded: a. Manually from Digital Counter and/or b. Magnetic Tape	*±0.14 percent
Propellant Temperature at Flow-meter	Resistance-Temperature Transducer	0 to 100°F	Analog Output Converted to Pulse Signal and Recorded: a. Manually from Digital Counter and/or b. On Magnetic Tape and/or c. On Strip Chart	±0.5°F
F-3 Fixture Propellant Tank Pressure	Strain-Gage-Type Pressure Transducer	0 to 300 psia	Analog Output Converted to Pulse Signal and Recorded: a. On Strip Chart and/or b. On Magnetic Tape and/or c. Manually from Digital Counter	±0.5 percent
Weigh Tank Pressure	Strain-Gage-Type Pressure Transducer	0 to 50 psia	Analog Output Converted to Pulse Signal and Recorded: a. On Strip Chart and/or b. On Magnetic Tape and/or c. Manually from Digital Counter	±0.5 percent
Diverter Valve Position	Potentiometer	---	Analog Output Recorded on Oscillograph	---

*Inplace Calibrated

TABLE II
N_2O_4 INPLACE FLOWMETER CALIBRATION SYSTEM ERRORS

*Flowmeter Size, in.	No. of Calibrations / No. of Flowmeters	No. of Propellant Data Points	System Component Error, 1σ, percent					Flowmeter** Precision 1σ, percent	Absolute System Error, 1σ, percent
			Deadweight	Load Cell	Pressure Correction	Temperature (SG)	Total		
2-1/2	5 / 1	56	±0.001	±0.100	±0.075	±0.041	±0.132	±0.129	±0.184
2-1/2	7 / 1	67	0.001	0.100	0.075	0.041	0.132	0.124	0.181
2-1/2	9 / 1	62	0.001	0.078	0.048	0.041	0.100	0.117	0.154
2-1/2	3 / 1	39	0.001	0.125	0.112	0.041	0.173	0.117	0.209
2-1/2	6 / 1	38	0.001	0.125	0.112	0.041	0.173	0.118	0.209
2-1/2	6 / 1	55	0.001	0.093	0.041	0.041	0.110	0.100	0.148

*Pottermeters

**Ref. to Equation of the Mean Line

TABLE III

AZ-50 INPLACE FLOWMETER CALIBRATION SYSTEM ERRORS

*Flowmeter Size, in.	No. of Calibrations	No. of Flow-meters	No. of Propellant Data Points	System Component Error, 1σ, percent					Flowmeter** Precision 1σ, percent	Absolute System Error, 1σ, percent
				Deadweight	Load Cell	Pressure Correction	Temperature (SG)	Total		
2	3	1	58	±0.001	±0.100	±0.144	±0.028	±0.178	±0.085	±0.197
2	7	1	70	0.001	0.100	0.144	0.028	0.178	0.132	0.222
2	9	1	70	0.001	0.175	0.024	0.028	0.179	0.132	0.222
2	3	1	36	0.001	0.186	0.048	0.028	0.194	0.095	0.216
2-1/2	6	1	45	0.001	0.186	0.048	0.028	0.194	0.106	0.221
2-1/2	6	2	55	0.001	0.093	0.024	0.028	0.100	0.139	0.171

*Pottermeters

**Ref. to Equation of the Mean Line

APPENDIX III
TYPICAL CALCULATION OF FLOWMETER CONSTANT (N_2O_4)

1. Load Cell Calibration

Counts, CT		Weight, lb
80881	≡	4147.3 lb
62951	≡	2908.4 lb

2. Load Cell Scale Factor

$$S.F. = \frac{4147.3 - 2908.4}{80881 - 62951} = 0.06909648 \text{ lb/CT}$$

3. Gross Propellant Weight

Load Cell Reading = 63802 counts

Gross Propellant Weight = (63802 - 62951) S.F. + 2908.4

= 2967.2 lb

4. Net Weight of Propellant

Weigh Tank Pressure = 27.8 psia

Correction = 13.5 lb

Net Weight = 2967.2 - 13.5 = 2953.7 lb

5. Totalized Flowmeter Cycles = 27943 cycles

6. Diverter Valve Transient Correction = +68.6 cycles (see Fig. 4)

7. Corrected Total Flowmeter Cycles = 27943 + 68.6 = 28011.6 cycles

8. Propellant Temperature at Flowmeter = 81.75°F

   Specific Gravity = 0.00120 (60-T) + 1.456*

   ∴ SG (81.75 °F) = 1.4299

9. Flowmeter Constant

$$K = \frac{(\text{Prop. Wt.})_{corr.}}{(\text{Flowmeter Cycles})_{corr}\ SG} = \frac{2953.7}{(28011.6)(1.4299)}$$

$$= 0.07374 \text{ lb-}H_2O/\text{cycle}$$

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*SG at 60°F from Lab Analysis.

APPENDIX IV
TYPICAL ERROR ANALYSIS CALCULATION FOR A FLOWMETER CALIBRATION SERIES

1. Precision of flowmeter data using data from a typical calibration series

Data Point	K, $\frac{\text{lb-}H_2O}{\text{Cycle}}$	$\bar{K}$, $\frac{\text{lb-}H_2O}{\text{Cycle}}$	δ%	δ^2%
1	0.07359	0.07360	0.013586	0.00018457
2	0.07346		0.190217	0.0361825
3	0.07358		0.027173	0.00073837
4	0.07376		0.217391	0.047258
5	0.07357		0.040760	0.00166137
6	0.07369		0.122282	0.0149529
7	0.07352		0.108695	0.0118146
n = 7			$\sum \delta^2\%$ =	0.112792

where

$$\delta\% = (K - \bar{K}) \times \frac{100}{\bar{K}}$$

and

$$1\sigma\% = \sqrt{\frac{\Sigma\delta^2\%}{n-1}} \qquad \sigma_{FM} = \pm 0.137 \text{ percent}$$

2. Estimated errors in weigh tank weight (1σ%) are

a. Deadweights 0.001%

b. Load cell 0.090%

c. Pressure Correction 0.041%

$$\sigma_{WT} = \sqrt{(0.001)^2 + (0.090)^2 + (0.041)^2}$$

$$= \pm 0.099 \text{ percent}$$

3. Estimated error in specific gravity due to propellant temperature measurement error (1σ) is

$$\sigma_{SG_{N_2O_4}} = \pm 0.041 \text{ percent (see Section 4.2.4)}$$

4. Best estimate of absolute error in flowmeter constant is

$$\sigma_T = \sqrt{\sigma^2_{FM} - \sigma^2_{WT} + \sigma^2_{SG}} = \pm 0.174 \text{ percent}$$

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13 ABSTRACT

The inplace flowmeter calibration system of Propulsion Engine Test Cell (J-3) is described, emphasizing the current equipment, calibration techniques, and the calibration results obtained. The system is a gravimetric pressure-fed propellant system which provides inplace calibration of turbine-type flowmeters with storable liquid propellants at the same temperatures, pressures, and flow rates experienced during rocket engine testing. Data from over 640 calibration data points have been statistically analyzed. Average absolute system errors for calibration with nitrogen tetroxide and a 50-50 hydrazine-UDMH blend were ±0.18 and ±0.21 percent, respectively, based on one standard deviation.

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